INSPECTION OF FLIP-CHIP EPOXY UNDERFILL IN MICROELECTRONIC ASSEMBLIES USING COMPENSATED LASER-BASED ULTRASONIC RECEIVERS

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INTRODUCTION

In the industrial community, there is a need for process control and inspection tools that can improve the efficiency, yield and performance of various manufacturing processes including bonds, surface treatments, case hardening, composites, metallurgy, microcrack detection, adhesion, remote temperature and thickness measurements. By performing the inspection on-line and in real-time, the possibility exists for closed-loop, in-process control. This can lead to reducing cost, labor, scrap, and machine downtime. Conventional ultrasonic methods can be employed to diagnose many materials, in that their acoustic properties are typically functions of the parameters to be ascertained. Present techniques, such as liquid immersion, jet-spray approaches, air-coupled and direct transducer contacting may be of limited use in many process-control applications, including those involving vacuums, high temperatures, plasmas, and workpieces with highly structured and complex surfaces.

Laser-based ultrasound [1], LBU, offers a means for long-standoff-distance ultrasonic inspection without destroying the workpiece and without physically contacting it. Optical probing enables inspection at precise locations on the part, with rapid reconfigurability, and with the potential for high-bandwidth sensing. Although laser-based ultrasound is well known as a potential remote inspection tool, it has yet to make a major impact in the manufacturing community. For example, in order to inspect rough-cut parts while undergoing relative platform motion, the receiver requires real-time compensation for both speckle and dynamic beam wander. Fabry Perot techniques [2] and single-speckle interferometry have been demonstrated, but require active stabilization (in the former case) or multiple-averaging (in the latter case).

In this paper, we describe several experiments using an advanced LBU-based receiver that can compensate for undesirable industrial noise sources, while enabling one to detect the desired ultrasound signals. Described below is the use of these receivers to remotely detect hidden voids in the epoxy underfill of semiconductor flip-chips, with the potential to inspect other flip-chip attributes, such as the integrity of solder bumps and ball-grid arrays. In general, such applications have promise in improving the quality control, yield, and reliability of critical components in the microelectronics industry as well as in the aerospace and automotive communities, via real-time process-control protocols. The possibility also exists for enhanced quality control via sensor suite systems, through the data fusion of LBU systems with other NDE schemes, such as thermal-wave imaging [3].

COMPENSATED LASER ULTRASONIC RECEIVERS

We have fabricated two different laser-based ultrasound receivers, both of which employ so-called adaptive photodetectors using real-time holographic means based on various nonlinear optical mechanisms to provide for the desired compensation [4]. In both cases, the compensated receiver enables a variety of industrial inspection needs to be realized in real-time, including weld-joint verification [5] and polymer matrix composite inspection via distributed probing of embedded opaque reinforcing SiC-based fibers [6]. These adaptive photodetection systems allow for the sensing of ultrasound over wide bandwidths (in the range of < 1 MHz to > 100 MHz) and wide fields-of-view, while compensating for undesirable industrial optical noise sources, including speckle, relative platform motion, and optical distortions encountered in the transmission of probe beams through multimode optical fibers. One receiver architecture employs a double-pumped phase conjugate mirror (DPCM) with heterodyne detection [5], while the other utilizes a mechanism called nonsteady-state photo-induced electromotive force (photo-emf) with homodyne detection [7]. In both cases, nonlinear optical interactions in single-crystal ferroelectric oxides or semiconductor crystals provide all-optical compensation of the optical distortions described above. Details of the physics, operational parameters and performance tradeoffs of these adaptive photodetectors are discussed elsewhere [6,7]. Suffice it to say, that the DPCM compensates for spatial wavefront distortions, yet passes temporal information, including the desired ultrasound as well as global piston phase shifts (such as whole-body motion, which represents an undesirable noise source in the present system), imposed onto a laser probe beam by the workpiece. The DPCM-based system therefore requires electronic post-processing (e.g., a phase-locked loop) to track out the low-frequency, global phase shifts. In addition, a DPCM system using barium titanate (as the nonlinear element) requires one to dwell on the workpiece, for $\approx$ 10 to 100 msec, so that the crystal can properly respond. A GaAs-based photo-emf detector, on the other hand, has been shown [7] to provide for substantial compensation of both spatial as well as global whole-body phase shifts, with much greater noise compensation bandwidth ($\approx$10 kHz) but, at present, has a predicted shot-noise limited sensitivity down by a factor of six relative to that of the DPCM-based system, the latter of which has been demonstrated to be near-shot-noise limited [8].

LASER-ULTRASONIC INSPECTION OF FLIP-CHIP UNDERFILL

In this section, we describe a proof-of-principle experiment that we performed using our LBU system for inspection of microelectronic circuit-board assemblies. Specifically, we inspected the quality of an epoxy underfill layer, which bonds a Si flip-chip to a circuit-board. The epoxy underfill is typically required to provide for enhanced bonding of the flip-chip to the substrate, as well as to prevent solder-bump microcracks from forming during normal operation in the field, in which case the components can be subjected to thermal cycling and mechanical vibrations. The epoxy bond is especially critical for larger-sized chips, say, in the multi-cm range, as well as in cases where there exists large differences in the thermal coefficients of expansion between the chip and the board on which it is mounted. During assembly and qualification, it is desired to remotely sense voids in the underfill, as their presence can lead to fracture of the bond and, thus, to reduced lifetime and potential component failure by virtue of a compromise in the integrity of the solder-bump's mechanical or electrical properties over time. The inspection can be accomplished off-line and, ideally, on-line during processing, so that potential voids can be detected early in the processing cycle. At the present time, a statistical sub-sample of the manufactured boards is removed from the assembly line and evaluated using conventional NDE techniques, such as x-rays or immersion ultrasound. LBU and thermal-wave imaging are two noncontact techniques presently under consideration to enable more rapid inspection, with the potential for 100% inspection and process control.

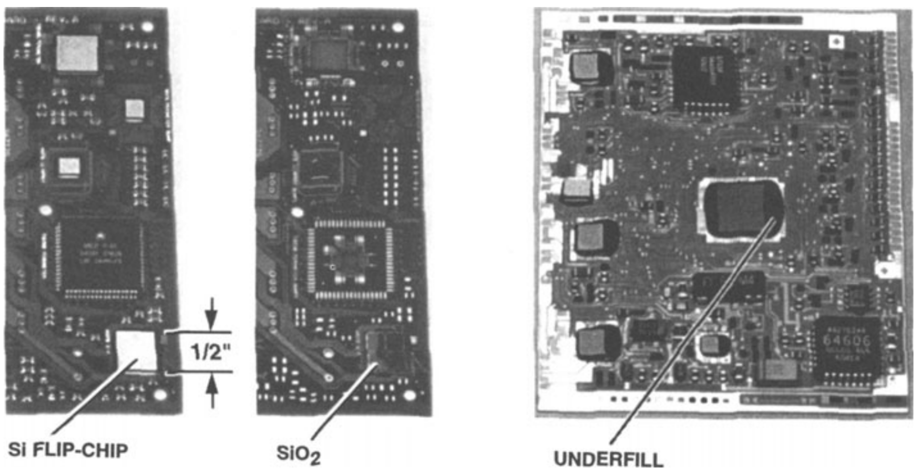

Figure 1. Photographs of typical circuit-boards with mounted Si flip-chips and epoxy underfill. Left: Conventional FR-4 board with Si flip-chips; Center: FR-4 board with SiO_2 witness slide in place of a flip-chip, visually revealing underfill voids; Right: Ceramic board with flip-chips.

Typical circuit-board sections containing flip-chips with epoxy underfill are shown in the photographs in Figure 1. Examples of substrates shown here include FR-4 boards and ceramic boards, both containing flip-chips and other mounted components. The FR-4 board on the right (i.e., the center photograph) was processed using a transparent SiO_2 witness sample in place of a Si flip-chip, with similar dimensions as the flip-chip. In this case, intentional voids were generated during processing so that one can clearly view the nature of the void formation, at least in these cases. A sketch of a flip-chip with voids in the underfill is shown in Figure 2, which also shows nominal dimensions. Given that the voids typically leave an air-gap in the epoxy layer, the acoustic impedance mismatch in the void region can be significant. That is, one would expect a significant qualitative difference in an ultrasound signature, when probing regions with a void present — a semiconductor */air/* substrate interface — versus a void-free region — a semiconductor */epoxy/* substrate interface.

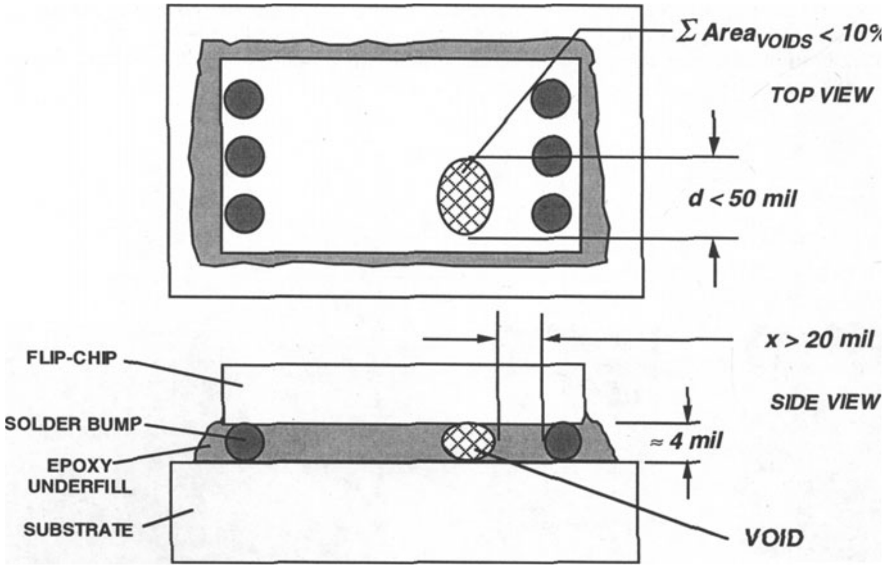

Figure 2. Sketch of a Si flip-chip on a board, indicating typical quality control parameters of epoxy underfill voids, including maximum void size, fill factor, and location.

In our demonstration, we employed a through-acoustic transmission mode using our LBU compensated receiver, as shown in Figure 3. For these initial experiments, boards without buried layers or vias in the flip-chip region were used, and the Si chips were circuit-free (in subsequent experiments, we will consider these additional realistic levels of complexity). The pitch-and-catch laser beams were directed onto opposite sides of the workpiece, and were aligned coaxially and anti-parallel. The ultrasound was generated on the backside of the substrate using a Nd:YAG Q-switched laser as the source, with a nominal energy of 50 mJ per pulse incident on the board, with a pulse width of about 7 nsec, and operating at 10 Hz. The laser output beam was unfocussed, with a spot-size on the order of 0.5 mm at the sample. At this optical fluence on the FR-4 board, we were operating in a mild ablative mode. In this case, moderate ultrasonic compressional waves are generated in the board by the pulsed Nd:YAG laser. The LBU receiver probe beam illuminated the topside of the Si flip-chip, using a frequency-doubled, diode-pumped Nd:YAG laser as the source, operating in a continuous mode (i.e., cw), with an output power of about 100 mW incident on the flip-chip. The probe beam was mildly focused to a spot-size of about 100 microns at the chip surface. Being above the bandgap of Si, most of the probe-beam photons were absorbed within a fraction of a wavelength (< 500 nm) from the surface of the flip-chip (whose thickness was about 0.5 mm). About 10% of the light was reflected back into our detection system, with a relatively large specular component present. No observable surface damage was observed on the chip by this probe beam. The reflected probe beam was collected by an optical train, and directed into our compensated receiver system. Both the DPCM-based system as well as the photo-emf sensor element were employed at different times during our experiments. For the measurements below, about ten laser shots were averaged per measurement location on the chip. In practice, one could adjust the system parameters so that a single-shot diagnostic can be realized.

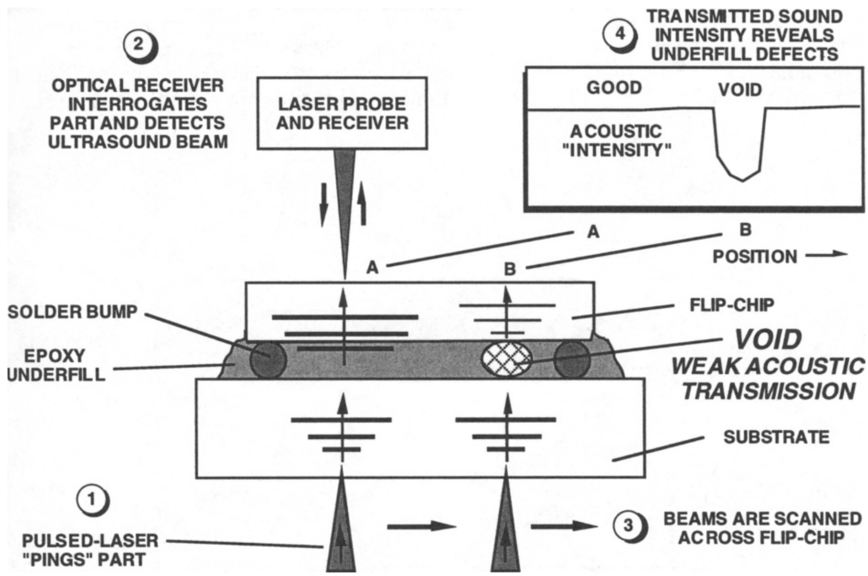

Figure 3. Basic geometry used for laser ultrasonic detection of flip-chip epoxy underfill voids.

An A-scan of the compensated LBU system output is shown in Figure 4. For this measurement, we employed the GaAs-based photo-emf detector [7]. In the figure, we show results for two cases: In one case, a sample was tested at a point where it was established by other NDE means that a good epoxy bond existed, whereas, in the second case, a typical void region was probed. Note that in the former case [Figure 4(a)], a sharply rising temporal feature is seen in the A-scan that appears on a time scale (about 0.3 μsec into the scan) which is on the order of the arrival of a compressional wave with an average speed of about 6 mm/μsec, assuming a total sample thickness of ≈ 2 mm (the approximate total thickness of the flip-chip, epoxy layer and FR-4 board). This arrival time and average ultrasonic speed of the combined materials is not unreasonable. On the other hand, for the case of a void (Figure 4b), no early arrival or sharp temporal features are observed. In fact, the first evidence of a surface displacement on the Si chip appears much later in time relative to the first case (about 1 μsec into the scan), with a much slower temporal evolution and lower amplitude. We attribute these features to a propagation delay associated with the longer path required by the compressional wave to diffract around the void region and find its way to the Si chip, coupled with an increased loss at higher acoustic frequencies. In any case, one can clearly see a dramatic qualitative difference in the acoustic signature for the good (i.e., void-free) versus the void regions.

We next placed this sample into our DPCM-based LBU system [5], which has an automated two-dimensional raster-scan capability, with computer-controlled data acquisition and color-encoded display output. The lasers for the generation and detection of the ultrasound have essentially the same operating characteristics as those used in the above-mentioned measurements. In Figure 5, we show results of this system, where a C-scan is shown. In this case, the sample was raster-scanned laterally over the entire surface area of a 1 cm by 1 cm flip-chip, with a 100 μm step size. Plotted is two-dimensional image of the data, with gray levels indicating the ultrasonically induced surface displacement of the flip-chip. At each interrogation point (or, pixel location) on the sample, the output displacement is displayed at a time-slot "window" set to that corresponding to the maximum amplitude observed in Figure 4(a) above (about 0.3 μsec into the scan). This plot clearly shows the areas on the flip-chip where void regions appear and also areas where a the epoxy bond exists. The small-scale spatial structure at the boundary of the void region indicates that the system is capable of resolving features on the order of 100 μm for our operating parameters, which is not a fundamental limit.

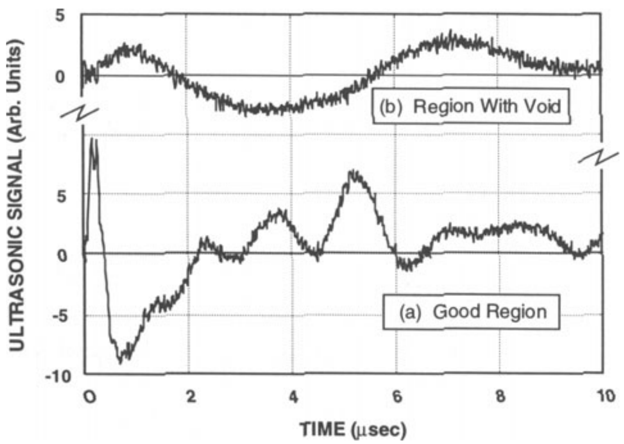

Figure 4. A-scan of Si flip-chip using a photo-emf-based LBU system. (a): Good (void-free) region; (b): Void region in epoxy underfill.

DISCUSSION

We have shown the ability of laser-based ultrasound to inspect microelectronic components and to reveal buried voids in the epoxy underfill of flip-chips on circuit boards. The system is capable of revealing the presence of voids, with an implied lateral spatial resolution on the order of 100 microns for our operating parameters. We have presented both single-point A-scans, as well as global C-scans, across the entire surface of a 1 cm by 1 cm Si flip-chip. Although the C-scan was generated by raster-scanning a single-point probe beam, we envision two different practical operating modes for such inspection systems. In one case, large-area generation and detection beams can be used to (respectively) sonify and sense the spatially integrated ultrasound over the entire surface region of the chip in a single frame. In this embodiment, one may be able to infer the presence of a threshold level of voids (e.g., a minimum relative area of defects) via level slicing of detected amplitude or via neural net classification. This mode can enable rapid go/no-go determination on an assembly line, on a single-shot basis (components rejected at this point can be evaluated for more details off-line, if desired). In another operational mode, an array of receivers can be configured [9] so that a single-frame image can be recorded of the chip. In this case, either each pixel can be independently displayed to yield a composite C-scan, or a phased-array output (with electronic steering) can be displayed, with enhanced spatial resolution capabilities. Note that, in the array embodiment, the desired mode of operation can be selected via programmable, onboard processors.

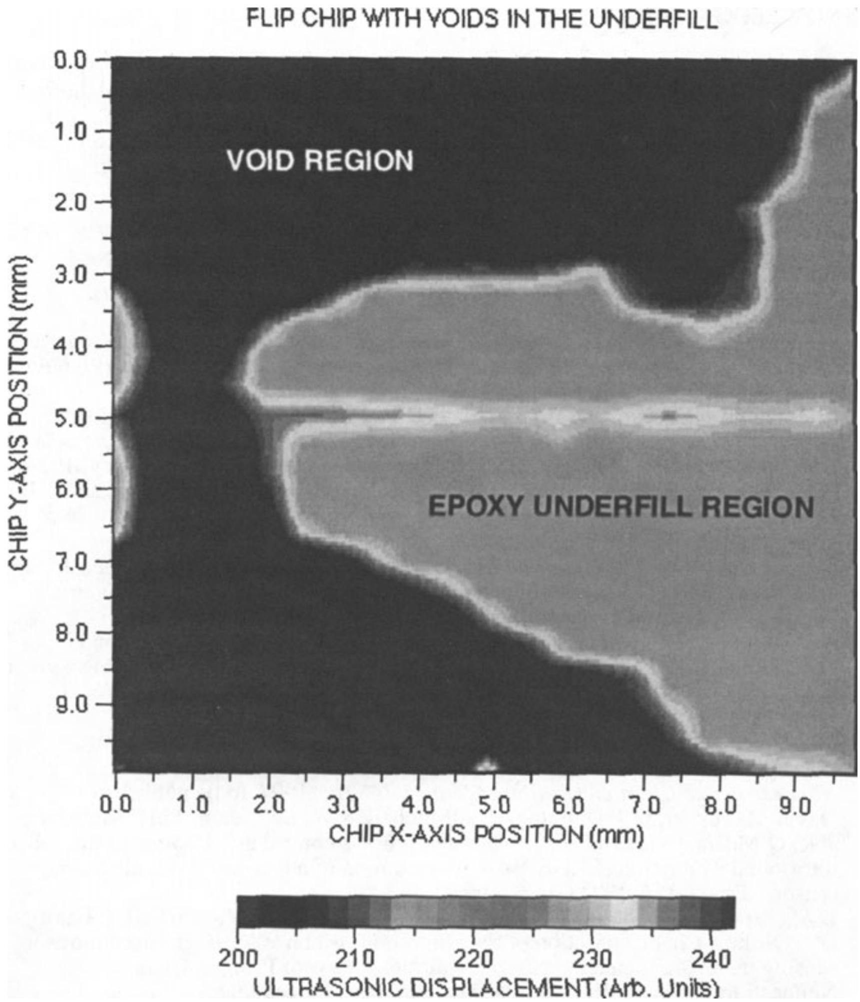

Figure 5. C-scan of a 1 cm by 1 cm Si flip-chip using a DPCM-based LBU system. Good epoxy underfill as well as undefill void regions are revealed.

We next intend to consider more complex structures, including multiple-buried layers within the mother board, as well as chips with detailed circuit features. In addition, we plan to consider different optical addressing architectures, as well as inspection of solder bumps and ball-grid arrays. In these cases, neural net processing may be required to classify the potentially complex, yet reproducible, spatio-temporal raw data. The LBU-based system described here can be easily reconfigured for rapid inspection of selected chips on a single board — as well as multiple-chip inspection on custom circuit-board layouts — all in a flexible manufacturing cell environment. In addition, other NDE schemes, such as thermal-wave imaging, can be used to augment the laser-based ultrasound diagnostic, so that a sensor suite can be realized with neural network or fuzzy logic processing of the fused-sensor data. One vision of this noncontact inspection diagnostic is that off-line, on-line, and eventual in-process control of microelectronics components can be potentially realized.

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